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Dyeing and colouring tests for fabrics

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Abstract: This chapter discusses the types of tests undertaken to evaluate fabric colour. The chapter first reviews the assessment of colour and colour change with detailed information on the visual and automated assessment. The chapter then examines in detail the factors involving colour fastness testing. Tests examined include light fastness, wash fastness, fastness to environmental factors, fastness to manufacturing processes, and tests specific to printed materials.

Key words: colour assessment, light fastness, wash fastness, colour fastness, staining, shade change.

9.1 Introduction: key issues in the testing of dyes and colours

A myriad of factors can affect the performance of a colour in a textile fabric. Colour performance may be assessed in many ways. These include levels of fading, change of hue, change of saturation and staining of other items. Knowing the correct test to perform and the most accurate measurement system to adopt can put the colour performance of a fabric ahead of the competitors. This chapter looks at the measurement of colour and colour change. It is designed to show how to adopt the correct test method to evaluate coloured fabric. It examines each type of test that can be performed and provides a detailed overview of variations between test methods.

9.2 Assessing colour and colour change

The assessment of colour and colour change is the most important part of testing dyes and colours. Incorrect colour measurement wastes time and money and can result in a substantial claim for compensation from a customer. Colour is measured by measuring the reflected light from a sample over a variety of wavelengths. Each colour has its own reflectance fingerprint defined by the percentage of light reflected at a given wavelength. A reflectance curve is measured in the visible region for a colour and is plotted as percentage reflectance (%R) versus wavelength. To simplify the description of colour, The International Committee on Illumination

(Commission Internationale de l'Eclairage or CIE) set a formulated system for the definition of colour in terms of 'tristimulus values' X, Y, Z. The tristimulus values of a sample represent the amounts of red (X), green (Y) and blue (Z) primary colours which are necessary to produce the 'colour' of the sample. They are determined from the reflectance value (R_λ), spectral radiant flux per unit area for the source light (E_λ) and the tristimulus eye sensitivity functions of the CIE standard observer ($\bar{x}_\lambda$, $\bar{y}_\lambda$ and $\bar{z}_\lambda$). The integration is usually performed over the wavelength (λ) range of 380–740 nm. A constant (k) is used to normalise the results. Equations 9.1, 9.2, 9.3 and 9.4 show the formulas for calculating the tristimulus values.

$$X = k \int_{\min\lambda}^{\max\lambda} E_\lambda \bar{x}_\lambda R_\lambda \mathrm{d}\lambda \tag{9.1}$$

$$Y = k \int_{\min\lambda}^{\max\lambda} E_\lambda \bar{y}_\lambda R_\lambda \mathrm{d}\lambda \tag{9.2}$$

$$Z = k \int_{\min\lambda}^{\max\lambda} E_\lambda \bar{z}_\lambda R_\lambda \mathrm{d}\lambda \tag{9.3}$$

$$k = \frac{100}{\int_{\min\lambda}^{\max\lambda} E_\lambda \bar{y}_\lambda \mathrm{d}\lambda} \tag{9.4}$$

In 1976 the CIE introduced the L^*, a^* and b^* and the cylindrical L^*, C^* and h chromaticity coordinates and these parameters are now widely used. These values are derived from the original X, Y, Z tristimulus values using equations 9.5, 9.6, 9.7, 9.8 and 9.9. L^* is defined as the lightness of the colour, a^* is the axis that extends from red (positive) to green (negative), b^* is the axis that extends from yellow (positive) to blue (negative), C^* is the intensity of chroma, h is the angle of hue, and X_n, Y_n and Z_n are the tristimulus values for the relevant standard illuminant and observer. Each of these parameters and the relationship between them is shown using the CIE colourspace described in Fig. 9.1.

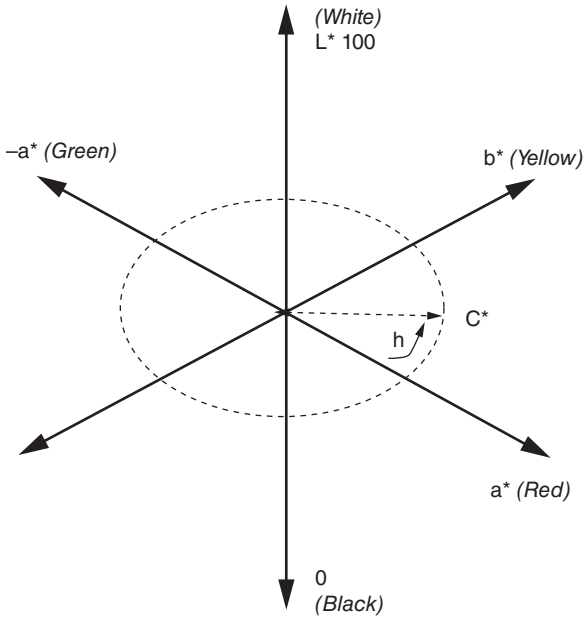
$$L^* = 116(Y/Y_n)^{1/3} - 16 \tag{9.5}$$

$$a^* = 500\left[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}\right] \tag{9.6}$$

$$b^* = 200\left[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}\right] \tag{9.7}$$

$$C^* = \sqrt{\left((a^*)^2 + (b^*)^2\right)} \tag{9.8}$$

$$h = \arctan\left(\frac{b^*}{a^*}\right) \tag{9.9}$$



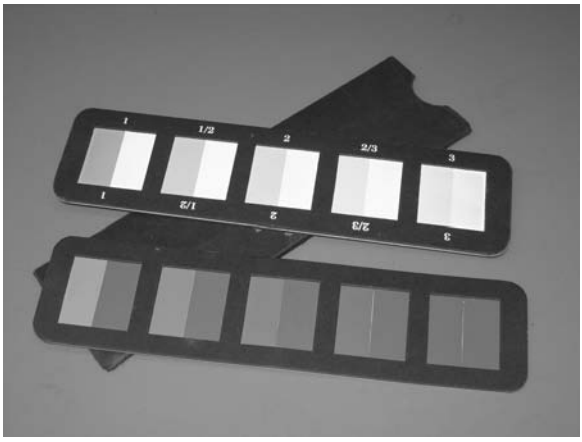
9.1 CIELAB colourspace.

Decomposition of dye molecules or physical removal of dye from the fibre are two mechanisms that cause colour change in a fabric. Where a single dye is removed or degraded, the result is generally a reduction of colour depth and/or a reduction of colour purity. The colour change in a commercial fabric can be a little more complex, as most dyes and dye recipes are made of a combination of dyes with different hues and concentrations. Each dye will behave differently under different environmental influences, therefore a change in colour could be caused by a change in hue as one dye is affected more than another.

There are two systems used for the assessment of colour change. These are visual assessment and computer aided assessment. Visual assessment has been in use since the performance of colour was first considered and is still used widely today. Visual assessment is a subjective measurement system and is significantly influenced by the person undertaking the assessment. The development of computer assessment systems and customers' requirement for repeatability and accountability are driving the shift to computerised measurement.

9.2.1 Visual assessment

The most well-known and used system of visual assessment is the grey scale. Grey scales are used as the rating system for most standard test methods



9.2 ISO grey scales.

as they are widely available, low cost and easily used. There are two types of grey scales. One set measures the change in shade of a coloured textile and the other measures the degree of staining in an adjacent fabric. The two grey scales are shown in Fig. 9.2. Grey scales have a rating of 1 to 5 with 1 being the worst colour performance and 5 being the best. Each rating can be split so that there are nine available ratings within the grey scale system.

The type of light used to illuminate the sample is important when visually assessing colour. Each light source produces a different emission spectrum and this influences the colour seen by the observer. Visual assessment of colour is normally carried out in a light box under a specified illuminant. The most common illuminants are artificial daylight, incandescent light, fluorescent light, horizon light, point of sale light and ultraviolet light. Each illuminant can then be broken down into individual types. An example is artificial daylight that has multiple source types including D50, D65 and D75. Most test methods specify the light source under which the samples should be rated. If the test method does not state the light source, a light source is agreed on and fixed by all stakeholders in the colour measurement.

The angle of the observer and the incident light are important in visual assessment. The illuminant light should hit the sample at 45°. This is achieved by resting the samples on a table set at a 45° angle to the light. This presents a perfect angle for the viewer to observe the samples perpendicular to the fabric surface. It is also important to exclude any light from external sources. Lights from external sources include room lighting or light from a window. Placing the light box in a dark room or placing a curtain around the light box will combat stray light.

The colour of the viewing surface is also important. Most standard test methods recommend a matt grey finish. The matt grey colour does not distract the viewer from the colour being assessed. It is important to keep the light box viewing surface clean and free of defects or imperfections. Damaged light box surfaces should be repaired with a paint that has the correct colour and gloss level.

9.2.2 Automated assessment

The use of spectrophotometers for fabric colour measurement has been adopted widely in the last 10 years. This technique has not changed much over the last 30 years; however, data collection and management of the spectrophotometer has. The development of low-cost high-powered desktop computers has allowed the quick acquisition, manipulation and quantification of colour information. Information obtained is both qualitative and quantitative, and can be efficiently stored for future reference or use. Information obtained using one spectrophotometer can be compared with results from another without any error. A spectrophotometer can provide a huge amount of measured and calculated information including ΔE^* values, multiple light source colour information, comparisons with measured or inputted standards, colour histograms of multiple batches, reflectance versus wavelength graphs and recipe advice.

CIELAB colour difference (ΔE^*) is the most common system used in automated colour assessment for defining a difference in colour. ΔE^* is the difference in colour between two samples (1 and 2), with the coordinates L^*_1, a^*_1, b^*_1 and L^*_2, a^*_2, b^*_2, and is calculated using equation 9.10. A CIELAB ΔE^* value of one unit represents the smallest colour difference that can be visually detected. Subsequent experience has shown that the visual detection limit is more like 0.8 of a unit. ΔE^* is most commonly used in fabric testing to electronically specify the change in shade or degree staining of a sample or adjacent fabric after fastness testing. Grey scales have been assigned fixed CIELAB ΔE^* values by the standard boards. The CIELAB-assigned ΔE^* values for each of the grey scales are reproduced in Table 9.1.

$$\Delta E^* = \sqrt{\left(\left(L^*_1 - L^*_2\right)^2 + \left(a^*_1 - a^*_2\right)^2 + \left(b^*_1 - b^*_2\right)^2\right)} \qquad 9.10$$

Colour data management has improved markedly since the development of automated assessment. Databases attached to the computer colour measurement systems allow for the efficient storage of colour data without the need to store the physical test sample. Specialised computer screens allow on-screen reproduction of the test standard and are accurate enough for a person to perform a visual assessment. Results can be sent worldwide using the Internet and appraised visually by the customer immediately after the test is completed.

Table 9.1 CIELAB ΔE^* assigned values for grey scales

CIELAB colour difference for fading		Colour fastness grade	CIELAB colour difference for staining	
Value	Tolerance		Value	Tolerance
0.0	<0.40	5	0.0	<1.10
0.8	0.40–1.25	4–5	2.2	1.10–3.25
1.7	1.25–2.10	4	4.3	3.25–5.15
2.5	2.10–2.95	3–4	6.0	5.15–7.25
3.4	2.95–4.10	3	8.5	7.25–10.25
4.8	4.10–5.80	2–3	12.0	10.25–14.45
6.8	5.80–8.20	2	16.9	14.45–20.45
9.6	8.20–11.60	1–2	24.0	20.45–29.05
13.6	>11.60	1	34.1	>29.05

9.3 Change in shade and staining tests

Change in the shade of a coloured fabric, or the staining of a fabric in the proximity of the coloured fabric, are performance problems associated with coloured fabrics. An example of change of shade is seen during light fastness testing of fabric. During exposure to light, most dyes degrade and change or lose their colour, causing a change of shade in the fabric. Staining of a fabric is seen during laundering when a white garment turns pink. This is due to migration of red dye from a garment that is also in the wash bath.

9.3.1 Reversible colour change

Some colours undergo reversible colour change. The light-initiated version of reversible colour change is called photochromism. Photochromism occurs because the photons of light striking the coloured surface induce a structure change in the dye instead of degradation of the dye. A change in dye structure results in a change in colour. After duration of no exposure to light the structure reverts back to its original form and colour. This type of colour change can also occur due to exposure to heat or chemicals.

9.3.2 Metamerism

Metamerism is the colour change seen in a coloured item because of different spectral emissions from different light sources. Each light source has its own emission spectrum (colour) so when a light source is projected onto a surface, the surface colour is influenced by the colour of the light. This produces a different colour to the observer for the same item when the light source type is changed. An example of this is the bluer tinge of a

coloured sample when observed under the fluorescent light TL84 compared to daylight. A standard light source is important when viewing, rating and specifying colour change to minimise the effects of metamerism.

9.3.3 Optical brightening agents

Optical brightening agents (OBAs) can cause serious error in the evaluation of colour and hence in the evaluation of colour fastness. OBAs are normally used to enhance the whiteness of a textile. They convert ultraviolet light into a wavelength in the visible spectrum. Most OBAs used for improving the white effect of a textile emit light in the blue spectrum, as most off-white colours reflect higher in the red/yellow end of the spectrum. The addition of blue to a white with a red/yellow base causes a flattening of the reflectance curve, resulting in the colour looking whiter. The addition of an OBA to a dyed colour will change the observed colour.

Most commercial laundry detergents contain an OBA to make whites washed in them look whiter/cleaner. All colours washed in these detergents adsorb OBAs, altering the colour even though the fabric's dye may not have been affected by the washing process. Most wash fastness test methods stipulate if OBAs are to be present in the wash liquor to limit the associated colour measurement problems. The presence of an OBA is easily detected in a fabric or detergent by placing it under an ultraviolet light source. The blue ultraviolet light will be reflected from the surface in the colour of the OBA.

Light fastness testing can be influenced by the presence of OBAs. OBAs have poor fastness to light and generally fade at a higher rate than most dyes. The chemical bond structure of the OBA provides the mechanism that allows ultraviolet light to be converted to visible light. This bond structure is easily changed by the ultraviolet light rendering the OBA colourless. OBA-induced light fastness problems are normally seen in whites and pastels.

9.4 Test standards

There are many different standard test methods for colour fastness testing of fabrics. The key standard setters for textile colour fastness are the Society of Dyers and Colourists (SDC) and the American Association of Textile Chemists and Colorists (AATCC). These two associations have spent many years developing standards and provide excellent information and advice on their websites. Other standard test setters in this area are the International Organisation for Standardisation (ISO) and the International Wool Textile Organisation (IWTO). These organisations provide standards to cover all facets of textile processing. Their colour standards are quite often based on

the SDC or AATCC equivalent. There are some country-based standard organisations, such as the British Standard (BS), American Standard Test Method (ASTM) and Australian Standard (AS). These are generally based on the ISO, SDC or AATCC test method with slight changes made to account for cultural or environmental differences. For example, it is not suitable to light fastness test fabrics for an Australian market under European natural daylight as the incident angle and intensity are different.

Consumers are increasingly looking for textile products that are environmentally friendly and have neutral health effects. Standard setters are creating new test standards to measure this. The Oeko-Tex Association has followed this theme and developed the Oeko-Tex 100 standard that is based around a human and environmentally friendly product. This standard looks at reducing harmful processing methods such as formaldehyde-based finishes. It also looks at minimising the environmental impact of textile processing by reducing environmentally harmful chemicals, waste and processes.

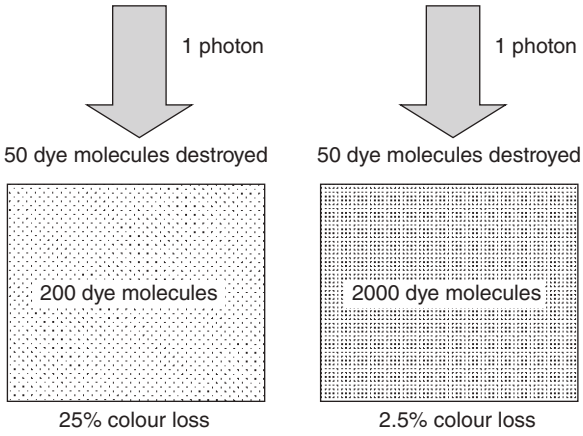
9.5 Light fastness

There are a large number of different light fastness tests available on the market. Each has its advantages and disadvantages. The most commonly used are the xenon arc and MBTF lamp; however, carbon arc and natural sunlight are also used. A fabric exposed to light is influenced by its depth of shade, the intensity of the light, the wavelength profile of the light, the temperature of the fabric, contaminants within the fabric, and the moisture content of the fabric. Other factors such as exposure cycling, exposure time and substrate colour change are also influential.

The light fastness rating system is based on the rate of fading of eight blue-dyed wool samples (blue chips) which are rated from 1 (poor) to 8 (excellent), with each successive standard dyeing taking twice as long to fade as the previous one in the series. The blue chips are placed into the light box with the samples to be tested and faded in parallel with the test samples. This is done as the light output of the light source can vary from test to test. Most test methods assess the light fastness when the fabric being faded exhibits a change in shade equal to 4 on the grey scale for colour loss.

9.5.1 Depth of shade

The depth of shade of a colour has a significant effect on the light fastness of a product. Light fastness is the degradation of a fixed number of dye molecules per exposure to a fixed intensity of light. A deeper shade is



9.3 Depth of shade effect on light fastness.

affected less than a pale shade, as a smaller percentage of the overall dye molecules are degraded per light exposure. Figure 9.3 represents this.

9.5.2 Intensity

Most accelerated tests for exposure to light fastness use high-intensity light to minimise the test time. High-intensity light can reduce the amount of time to undertake the test, though it can also influence the result. Higher-intensity light generally results in higher sample temperatures, causing the reaction rate of dye degradation to increase. The rate of dye degradation with respect to temperature is not linear. At elevated temperatures one dye may fade at a quicker rate than another, giving a hue change not seen at lower temperature fading.

Most high-energy light sources have varying intensity depending on the age of the light source. Most have a run-in time before they can be reliably used and most have a set number of hours of use before they should be replaced. Most standard test methods have details of the run-in times and maximum number of running hours of a light source.

9.5.3 Wavelength

Different light sources have a different wavelength profile. Some are close to natural daylight; however, the majority have wavelength peaks of high intensity that are different from natural daylight. Daylight itself varies depending on the latitude of the viewer and the time of the year. The wavelength of the incident light on the dye bonds significantly influences the rate of degradation of those bonds. A wavelength profile different from

natural daylight could show an increased or decreased fastness rating, depending on the dye tested.

9.5.4 Temperature

The temperature of the test sample will influence the rate of light-induced degradation of a dye. Most light fastness tests have black body temperature measurement and a method of sample cooling so that temperatures do not become too high. High-intensity light sources produce increased sample temperatures, so increased cooling capacity is required to lower test temperatures. Tests for automotive fabrics are conducted at higher test temperatures, as the fading environment within a car interior can involve elevated temperatures not normally seen in the fading environment for clothing.

9.5.5 Moisture

The level of moisture in the fabric can influence the rate of colour degradation. The presence of moisture during a light fastness test can lead to the generation of peroxide radicals that significantly influence the results of the test. Moisture content is hard to control as the heat from the light source tends to decrease the moisture content of the fabric. Moisture levels can be monitored during a test by using azoic-dyed cotton with specified fading properties which vary with the amount of relative humidity. Some tests involve starting the test samples wet to simulate line drying of fabrics. Some tests involve intermittent jets of water to simulate rain on an exterior fabric. Tests that involve the use of water sprays are generally referred to as weathering tests.

9.5.6 Contaminates

Some fabrics are exposed to chemical contaminates when they are in use. These contaminates can include salt and chlorine. Tests have been developed to intermittently spray the fabric with chemical-contaminated water during the test. Like water, chemical contaminates can become involved in the chemical degradation of the dye molecules.

9.5.7 Test cycling

Sometimes exposing the fabric to a light source for a fixed duration is not enough to see the behaviour of the colour. Cycling of the light source on and off is sometimes used to simulate night and day. Some dyes can degrade to a certain point and degrade no further with continuous exposure to light.

Switching the light off for a period of time allows the energies within the dyes to return to their ground state. This can initiate a second round of fading when the light is restarted.

9.5.8 Substrate colour change

Substrate colour change is quite common in pastel wool colours. Wool initially photo-bleaches when it is first exposed to light; however, it yellows quite rapidly with continued exposure. The colour of the dye might not be affected by the incident light, though the change of the substrate colour will result in a change in the fabric shade.

9.5.9 Photochromism

Photochromism is commonly caused by exposure to light. The level of photochromism can be determined by placing a colour in an intense light source for a short period of time and then immediately rating it for colour change. If subsequent return to normal colour occurs after conditioning in the dark then the colour is photochromic. Some colours require a period of time to condition in the dark after light fastness testing before colour assessment can be conducted to avoid any photochromic effect.

9.6 Wash fastness

Consumers launder their fabric at some time in the lifespan of the textile. Change of colour or staining of another garment during laundering is generally immediately evident to the consumer and has a high impact on consumer satisfaction. Like light fastness testing there are a huge number of different iterations of the wash fastness test. The wide variety of test methods have mostly arisen due to the variety of washing methods available, cultural practices, the material being washed, and the end use of the product. The development of detergents and bleaches has influenced the development of new wash fastness test methods.

It is important when selecting a wash fastness test method to choose one that best simulates the washing environment of the fabric's end use. If no end use has yet been selected then it is important to clearly label the level of wash fastness testing that has been conducted on the fabric. The most common washing methods in use today are dry cleaning, hand washing, gentle machine washing, machine washing, permanent press and industrial laundering. Each of these methods has one or more wash fastness tests to determine fabric colour suitability. Table 9.2 shows the variety of conditions in the first five ISO wash fastness tests for domestic and commercial washing.

Table 9.2 The first five ISO wash fastness test conditions

Test	Temperature (°C)	Time (min)	Number of steel balls	Chemicals
ISO 1	40	30	0	Soap
ISO 2	50	45	0	Soap
ISO 3	60	30	0	Soap + Na_2CO_3
ISO 4	95	30	10	Soap + Na_2CO_3
ISO 5	95	240	10	Soap + Na_2CO_3

Each of these tests would be carried out at a 50:1 liquor ratio in a 2.0 litre wash wheel vessel with 5.0 g/l standard soap solution.

9.6.1 Equipment

Most wash fastness tests are carried out in enclosed 2000 ml vessels that are rotated at a constant speed and at a constant temperature in a wash wheel. An Atlas laundrometer is the most common make of equipment used for undertaking this test. The wash wheel is commonly referred to as a laundrometer. The fabric, adjacent material and wash liquor are placed into the test vessel before it is sealed. Some tests require the addition of stainless steel balls or discs to the wash liquor to increase the severity of the test.

9.6.2 Soaps and detergents

In a wash fastness test the soap or detergent is used to remove unfixed dye from the fabric. The use of a soap or detergent can also cause a breakage of bonds that hold the dye on the fibre. The pH of the soap or detergent has a major influence on the movement of dye from the fabric into the wash liquor and from the wash liquor to adjacent fabrics. Since the invention of detergents, the blend of chemicals used for domestic and commercial laundering has become quite complex. Most detergents contain mild oxidising agents, softeners, optical brightening agents, salts and other fillers. These detergent auxiliaries can increase the amount of dye removed from the fabric and in the case of oxidising agents cause degradation of the dye molecules. The dispersing nature of different detergents can also reduce the level of cross-staining to an adjacent fabric as the dye is held in the wash liquor by the detergent and is not allowed to redeposit. Some test detergents are specifically designed to contain bleaches and bleach activators like sodium perborate tetrahydrate and tetraacetylethylenediamine (TAED).

Table 9.3 SDC multifibre strips

SDC multifibre DW	SDC multifibre TV
Secondary cellulose acetate	Triacetate
Bleached unmercerised cotton	Bleached unmercerised cotton
Nylon 6,6	Nylon 6,6
Polyester (Terylene)	Polyester (Terylene)
Acrylic	Acrylic
Unbleached wool	Viscose rayon

9.6.3 Test fabrics

Cross-staining of a third-party fabric is assessed using an adjacent fabric fixed to the fabric test sample. Adjacent fabrics come in many types and many forms, including single-component woven fabrics and multifibre woven fabrics. The single-component adjacent fabrics commonly used are cotton, wool, polyamide, acrylic, viscose rayon, polypropylene and polyester. Tests involving single-component adjacent fabrics have the adjacent fabric fixed to one or both sides of the fabric test sample. Sometimes a different adjacent fabric composition is used for each side to show staining on two fabric types. Nylon 6,6 is commonly used in staining tests as it tends to scavenge any free dyestuff from the wash liquor better than any other fabric composition.

Multifibre adjacent fabrics allow staining exposure to a range of different fabric types during one test. The most common supplier of multifibre fabric is the Society of Dyers and Colourists (SDC). The SDC produces two multifibre fabrics; one contains wool and one does not (Table 9.3). Multifibre fabric is affixed to one side of the test specimen and the other side is normally a polypropylene fabric in a staining test.

9.6.4 Agitation time

The agitation time of a laundering test can significantly affect the test results. Short test times limit the dissolution of unfixed or poorly fixed dye into the liquid or onto the adjacent fabric. The dye has more time to escape from the fibre and to migrate onto the adjacent fabric in longer tests. Longer test times can allow the dye to deposit on and migrate into the fibres of adjacent fabrics following a mechanism similar to dyeing, leading to an increase in the level of staining.

9.6.5 Temperature

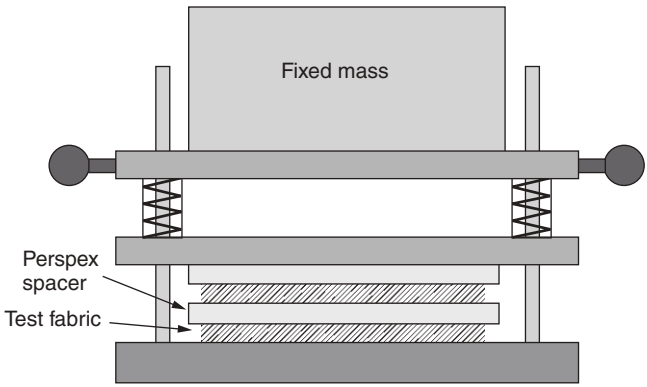
The results of a wash fastness test are significantly influenced by the test temperature. Lower test temperatures are used where the end-use fabric

requires low-temperature washing. Low-temperature washing is normally seen for delicate fabrics like wool, silk and viscose. Low test temperatures limit the migration of dye from the fabric surface and generally cause low levels of staining on adjacent fabrics. There is not as much energy available at low temperatures, and energy is needed for the dye to attach and penetrate the adjacent fibre. High test temperatures should be used for fabrics that could be warm or hot washed during their lifetime. Higher test temperatures provide the energy required to swell fibres and migrate dyes. At higher temperatures adjacent fabrics are more likely to be stained by any free dyes in the wash liquor. Fabrics that are going to be used in a product destined for industrial laundering are generally tested at higher temperatures than normal, as industrial laundering temperatures are generally higher.

9.7 Fastness in relation to environmental factors

Wash fastness testing looks at the loss of colour or staining of adjacent fabrics due to laundering. However, there are numerous other environmental influences that may cause colour performance problems, most commonly perspiration. Perspiration from the human body is a complex chemical containing large quantities of salts; depending on the human metabolism, it can be either acidic or alkaline. Most of the tests for perspiration fastness are based on a solution containing the chemical histidine.

The fabric and adjacent fabric are generally soaked in the test solution before being placed under pressure in a perspirometer and incubated at body temperature for a period of time. Figure 9.4 shows an illustration of the general layout of a perspirometer. The test fabrics with adjacent material attached are sandwiched between Perspex plates under a fixed mass.



9.4 Perspirometer.

The perspirometer is also used for other tests including testing for fastness to water and seawater. Fastness to water testing simulates the effect of leaving washed fabric sitting in a wet pile after laundering. The staining assessment is the most important part of this test, as the colour can easily transfer from article to article under wet pressurised conditions. Fastness to seawater looks into the same effect as fastness to water but includes sodium chloride in the test solution, as salt can cause increased migration of dyes.

Fastness to chlorinated water is used to evaluate the colour fastness of swimwear, towels, deck furniture webbing or other articles that may be exposed to large amounts of chlorinated water. The test is normally carried out using a wash wheel under similar conditions to a wash fastness test; however, the temperatures used are selected to reflect pool water. It is important to check the active chlorine levels of the test solution before the test, as chlorine can reduce in strength over time.

Spot testing is used to determine the effects of spotting chemicals onto a fabric to remove a point stain or to simulate spot staining. An adjacent fabric can be fixed behind the spot to assess staining; however, the test is normally used to assess spot migration of the dyes within the fabric. Spotting tests include fastness to water, acid, alkali, dry cleaning fluid, and white spirits.

Fastness to rubbing is used to ensure that fabrics do not transfer their colour when rubbed against another layer of fabric. This test is also known as crocking and is carried out using a crockmeter. A crockmeter is a piece of equipment that applies a constant force on the test fabric against the tested specimen as it is rubbed back and forth. Rub fastness is carried out with either a dry or wet cotton fabric that is rubbed against the surface of the dyed fabric to remove unfixed dyestuff. Rub fastness using a wet test fabric tends to show higher colour transfer than when using a dry test fabric.

9.8 Fastness in relation to manufacturing processes

There are a range of tests that are based around the mechanical processing of textile fabrics during and after the manufacturing process. The tests are described only briefly here as books on processing, product circulars and test standards describe these test methods more specifically. The tests for processing are based around three main concepts: the application of heat, gases and chemical processes.

9.8.1 Colourfastness to heat

Heat-based tests look at the change of colour due to heat. Some dyes sublime under extreme heat and can be evaporated from or heat-transferred

from the fabric. Some dyes are degraded by extreme heat and can change or lose their colour. The presence of moisture during heating can increase swelling of the fibre and thus increase the transfer of colour into an adjacent fabric. Heat can be applied in various ways, so the test selected must reflect the way in which the heat is applied. The four ways in which a heat can be applied are dry heat without pressure, steaming without pressure, dry heat with pressure, and steaming with pressure. The test for dry heat without pressure is used to simulate drying of fabrics. The test for steaming without pressure looks at the colour change due to steam relaxation or steam setting. The test for dry heat under pressure is a test to simulate hot pressing, ironing and calendaring. The test for steaming with pressure is used to replicate steam pleating, steam pressing and decatising.

9.8.2 Colourfastness to chemical processing

There are a large number of chemical processes that expose coloured fabrics to chemicals. Most chemical processes in manufacturing involve chemical finishes applied to the fabric after dyeing. A large number of these finishes have specific tests defined by the company that look at the level of colour change occurring during the finishing process. Chemical finishes can also affect light fastness and rub fastness results. Therefore for some fabrics these parameters should be measured after the finish has been applied.

During manufacture a dyed fabric may be exposed to a number of chemicals. Standard test methods have been developed to assess the changes that these factors can cause. Testing includes bleaching with different bleaching agents including chlorite, hypochlorite and hydrogen peroxide. Wet processing of fabrics such as milling, carbonising and crabbing can also affect fabric colour. The test for crabbing is also referred to as potting, as it involves boiling the fabric under tension for a period of time.

9.8.3 Gas exposure

There are a whole range of tests that are based around drying fabrics. The tests for oxides of nitrogen and burnt gas fumes are used to evaluate the effects of inefficient and badly regulated direct-fired drying equipment. Ozone is also a chemical that is generated in the environment or during combustion. Ozone can rapidly break down dye, so there are a number of standards that relate to the effects of ozone in the presence of a textile fabric.

There are also tests that look at the influence of residual chemicals in the fabrics during drying. The most common of these tests look at the presence of residual hardness salts, acid and alkali. Specific tests can also be conducted

to look at the effects of aftertreatments applied during or subsequent to the drying process.

9.9 Printing tests

The colour fastness of printing is slightly different from that of dyeing, as most printing techniques use a pigment to colour the surface of the fabric generally by forming a pattern on the fabric. The pigment is bound to the fabric surface using a polymer binder, most commonly acrylic. The main problems associated with prints are poor registration of the pattern, wicking of some or all of the colours and poor rub fastness. Printing is commonly done over the top of a previously dyed fabric and the printing process and chemicals can have an effect on this colour. The printing process can also affect fabric properties other than colour and these should also be measured. Most of the standard tests used for assessing colour in dyed goods are also used for printed goods.

9.9.1 Registration

Registration refers to the alignment of a single print colour on the fabric with reference to the fabric and other colours in the print. A malfunction or poor setup of the printing process can result in poor registration of a print. This will be seen in the final product as a misalignment of part or all of the individual colours of the print. Testing for registration can be conducted visually with deviation from registration measured with a ruler or callipers. The development of image processing software has resulted in several good automated print registration test apparatus being available in the market.

9.9.2 Wicking

Wicking is the transfer of some or the entire print colour along the fibres in a fabric due to a capillary action. Wicking can be seen as a reduction of sharpness of a printed edge and can be assessed visually or with the same software as is used for the testing of print registration. Sometimes the printing ink can cause bleeding of the fabric base colour. Bleeding of the base colour looks blotchy along the edge of the print or, when printing is done in a garment, a transfer of dye onto the fabric occurs adjacent to the print face.

9.9.3 Rub fastness

Rub fastness is of significant importance to prints, as the colour is provided by a pigment that is fixed to the exterior of the fibre. The pigment on the

surface of the fabric is the first component to come under attack when a fabric is rubbed or abraded. Crocking is a simple method for determining fastness to rubbing. The standard 10 cycles employed in the crocking test may not be enough to break down a faulty pigment binder system, so some rub fastness test methods involve an increased number of rubbing cycles. There are test methods and testing equipment developed that have an increased abrasive effect on the fabric surface. These include oscillating drum, wire mesh and emery abrasion testers. Each of these testers abrades the surface more than the crock meter and they are used for textiles that require high resistance to abrasion such as military fabrics.

After rub fastness testing the rubbed surface is often appraised for colour change or frosting. Frosting is common in prints and is the pigment rubbing away from the surface of the fabric exposing the natural fibre colour below. This can also be called fibrillation, as single fibres poke through the surface of the print. Frosting is easily identified in a loss of depth of shade of the print.

9.9.4 Fastness to steaming

Most prints are steamed to improve penetration into the fabric or to assist in fixation of the dye or binder system. It is important that dyes or pigments used in the printing industry are fast to steaming. The test should not just be limited to the effect of the steaming on the print but should be expanded to include the fabric base colour. A change in fabric base colour can occur even though the print is unaffected. The tests undertaken for steaming are generally the same as the tests explained earlier for steam without pressure.

9.9.5 Light fastness testing

When testing light fastness it is important to assess all of the colours in the print. Light fastness test samples should be selected to maximise the area of each of the colours within the print, and more than one light fastness sample per print may be required to achieve this. Pigments generally have better light fastness than dyes, as the chromophore does not need to be selected to fit into the fibre matrix or to have specialised bonding and solubilising groups.

9.9.6 Plastisol prints

Plastisol prints pose their own unique fastness problems. Inaccurately cured pigment can result in cracked and peeling prints or bleeding of the colour into other fabrics. Prints can be tested for curing by a simple domestic

washing followed by a tumble dry. Other curing tests can involve the use of solvents and pressure. The print is spotted with small amounts of solvent and then pressed against a fabric to assess the colour transfer. Dry heat is normally used to apply a plastisol print, so fabrics should be evaluated for dry heat in pressing to ensure that there is no colour change to the fabric base colour.

9.10 Applications

There are many different applications for the testing of coloured fabrics. The textile colourist utilises colour testing to confirm a colour matching formula before it is used in manufacture. Most textile mills will implement quality control testing of colours during manufacture to reduce the chance of faulty work being processed further than it needs to be. It is hard to improve the wash fastness of a fabric that has been cut into a garment.

It is important to measure the colour fastness properties of a dyed fabric after manufacture. Most customers require a quality control certificate for the fabric that they are purchasing to confirm that it meets their target limits. Testing will highlight possible problems and avoid despatch of under-specification fabric. A manufacturer should measure a fabric that has come from a supplier or commission dye house if the fabric does not already have a set of test statistics. When a fabric does come with test results, it is advisable to double-check test results for the first few deliveries from a new supplier and then randomly audit deliveries as purchases continue. Suppliers that have their own test laboratories can be production-biased when rating fastness results and can pass samples that have not met the testing requirements. Double-checking the results will give confidence in the skill and accuracy of the supplier's test house.

Quite often a manufacturer will be interested in replicating a competitor's product. Careful testing of the product can reveal the type of colouration method used and the level of fastness required to duplicate the product. Testing results of a product can be used to exploit the marketing potential of a product. The development of machine wash fast colours was originally a strong selling point for a textile product. Proof of meeting Oeko-Tex 100 environmental and health standards is an example of a new selling point that can be confirmed by accurate product testing.

9.11 Future trends

In the future we will see increased use of electronic measurement of colour and colour fastness test results. The development of data handling, transfer and storage has revolutionised the way in which test results are measured and conveyed within the mill and to the customer. The Internet

transfer of colour and colour details is becoming adopted by more processors and customers, and speeds up the test path as a customer can approve a colour test just minutes after it has been conducted. The use of fuzzy logic mathematics helps to analyse all of the testing data and enables the manufacture to optimise processing and reduce reject rates.

Consumer requirements for environmentally friendly, neutral health effect and neutral environmental impact textiles will increase. Some companies are leading the way by meeting standards like Oeko-Tex 100; however, more stringent standards will be developed. Environmentally friendly coloured textiles will see significant development in test methods and accreditation over the next decade.

9.12 Sources of further information and advice

Society of Dyers and Colourists, www.sdc.org.uk
American Association of Textile Chemists and Colorists, www.aatcc.org
Pantone, www.pantone.com
Oeko-Tex Association, www.oeko-tex.com
International Organisation for Standardisation, www.iso.org
International Wool Textile Organisation, www.iwto.org
Ecological and Toxicological Association of Dyes and Organic Pigment Manufacturers, www.etad.com

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10

Testing intelligent textiles

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Abstract: Intelligent textiles represent the next generation of fibers, fabrics and products made from them. In the last decade, research and development in smart/intelligent materials and structures have led to the birth of a wide range of novel smart products in aerospace, transportation, telecommunications, homes, buildings and infrastructures. New methods of testing and evaluation procedures for testing intelligent and smart fabrics are becoming extremely important in the industry as the future lies in these textiles. In this chapter the principles and some of the important test methods for testing intelligent fabrics, such as shape memory fabrics, phase change materials and self-cleaning fabrics, are explained.

Key words: Intelligent testing, testing shape memory fabrics, testing phase change materials, electronic response testing, self-cleaning tests.

10.1 Introduction: role of intelligent textile testing

Today's textile industry is in the transition zone between a traditional textile production and the realization of highly focused design and production of added value textiles. The innovative field of smart and intelligent textiles is becoming increasingly popular and commercially successful because it combines product use with new material properties. Intelligent textiles represent the next generation of fibers, fabrics and products made from them. They can be described as textile materials that think for themselves. This means that they may keep us cool in hot environments or warm in cold conditions. Apart from the clothing sector, they are gaining popularity in various other fields, such as biomedical materials, electronics, the automobile industry, protective clothing, etc. They provide ample evidence of the potential and enormous wealth of opportunities still to be realized in the textile industry, in the fashion and clothing sector, as well as in the technical textiles sector. Integrating intelligent textiles into clothing is an exciting new field, which opens up a vast arena of applications. With revolutionary advancements occurring at an unprecedented rate in science and electronics, the possibilities offered by wearable technologies are tremendous. As the technologies become more refined so that complex systems can be embedded unobtrusively in everyday clothing they will soon be more and

more commonplace in commercial products. It is anticipated that the results will likely support the possibility of creating and producing 'intelligent clothing' and smart technologies in the clothing sector, and offer services in the integration of intelligence with clothing.

Working closely with the clothing industry will develop the base that is needed to offer developments in intelligent clothing with huge commercial potential at minimum risk. At a later stage of development, this is likely to create more solid product assortments. Those experienced in the industry expect that technologies in smart clothing will be launched in the market within the next five to ten years. Hence there exists an absolute necessity to understand these new fabrics and their technologies. Testing of fabrics hitherto limited to traditional fabrics, such as apparel, home furnishings and some varieties of technical textiles, may not help in the long run in understanding the properties of these new fabrics. New methods of testing and evaluation procedures for testing intelligent and smart fabrics are becoming extremely important in the industry as the future lies in these textiles.

10.2 Understanding existing materials and technologies

Textiles are used in a number of applications from apparel to technical textiles. The era of technical textiles has opened up a new challenge for design of new type of textiles for protective clothing, sports, pleasure, social promotion, etc. Before any such new development takes place it becomes absolutely important to understand the existing types of textile fabrics and their technologies. Currently fabrics are being used in protective clothing for protection against vagaries of weather, fire, severe thermal effects, etc. Technical textiles in the form of fabrics are widely used in a number of industries such as aerospace, military, sports, composites, agriculture, automobiles, etc. A large variety of fabrics are being used in geotechnical applications as geotextiles for reinforcement of soil, filtration and drainage purposes. The medical field has opened up new avenues for functional textiles for biomedical applications such as sutures, scaffolds, stents, etc. All the above existing textiles form the basis for the new developments. But the future trends lie in making a fabric more multifunctional so that it acts as a smart fabric, finding its own applications in new environments.

The textile and garment industry in the developing countries is much more challenging. The companies that concentrate on specialty products and technical development still believe in the future. In order to survive, the companies have to follow the developments in the market and must come up with new ideas with high added value.

10.3 Development of new products

Intelligent textiles and wearable technology are of great interest today. The new ideas and products developed in this area are expected to be the winners of tomorrow. Various types of fibers, textiles and garments that have interactive properties, i.e. that react with logic to information received from the environment, are so-called intelligent textiles. By integrating electronics and sensors in textiles, new types of cross-scientific products can be created.

The most important intelligent materials at present are phase change materials, shape memory materials, chromic materials and conductive materials. Phase change materials are compounds which melt and solidify at certain temperatures and in doing so are capable of storing or releasing large amounts of energy. Phase change materials can be incorporated into a thermal storage system in order to store daytime solar energy to provide space heating. Shape memory materials are those that can revert from the current shape to a previously held shape, usually due to the action of heat. When these shape memory materials are activated in garments, the air gaps between adjacent layers of clothing are increased in order to give better insulation, thus conferring greater versatility in the protection of the garment against extremes of heat and cold. Chromic textiles change their color reversibly according to external environmental conditions; for this reason they are called chameleon fibers. The color change in these materials can be stimulated by light, heat, electricity, pressure and energy, liquids or electronic beam. Conductive fabrics combine the latest high wicking finishes with high metallic content in textiles that still retain the comfort required for clothing. With the addition of nickel, copper and silver coatings of varying thickness, these fibers provide a versatile combination of physical and electrical properties for a variety of demanding applications. For example, the thousand-fold increase in thermal conductivity of metal over conventional polymers used in clothing offers sports apparel with the minimum of thermal insulation (Karthik, 2006; Murthy *et al.*, 2003).

In the last decade, research and development in smart/intelligent materials and structures have led to the birth of a wide range of novel smart products in aerospace, transportation, telecommunications, homes, buildings and infrastructures. Although the technology as a whole is relatively new, some areas have reached the stage where industrial application is both feasible and viable for textiles and clothing (Tao, 2001). Many exciting applications have been demonstrated worldwide. Extending from the space program, heat generating/storing fibers/fabrics have now been used in ski wear, shoes, sports helmets and insulation devices. Textile fabrics and composites integrated with optical fiber sensors have been used to monitor the

soundness of major bridges and buildings. The first generation of wearable motherboards has been developed, which have sensors integrated inside garments and can detect information regarding injury to and health of the wearer, and transmit such information remotely to a hospital. Shape memory polymers have been applied to textiles in fiber, film and foam forms, resulting in a range of high-performance fabrics and garments, especially sea-going garments. Fiber sensors, which are capable of measuring temperature and strain/stress, and sensing gas, biological species and smell, are typical smart fibers that can be directly applied to textiles (Boczkowska and Leonowicz, 2006). Conductive polymer-based actuators have achieved very high levels of energy density. Clothing with its own senses and brain, such as shoes and snow coats which are integrated with Global Positioning System (GPS) and mobile phone technology, can tell the location of the wearer and give him or her directions. Biological tissues and organs such as ears and noses can be grown from textile scaffolds made from biodegradable fibers. When integrated with nanomaterials, textiles can be imparted with very high-energy absorption capacity and other functions such as stain proofing, abrasion resistance, light emission, etc. Incorporating electronic devices into textiles leads to a new branch of science called textronics (Gniotek and Krucińska, 2004). This is a new research area which so far has not produced very many applications, though expectations are high.

The diversity in the application of electronic textiles (e-textiles) is increasing and becoming interesting. The textile clothes, being lightweight, strong and bendable, can be stretched over any frame into a desired shape with a concept to change the size, shape and style of clothes by weaving 'muscle wires' into the fabric. The wires are made of shape-memory alloys that change length according to the small current passed through them. Electronic wires and sensors woven into the fabric can perform the function of listening for faint sounds. That means people resting in tents or camouflage nets may hear the distant sounds of vehicles or stepping/movement of people, animals, enemies, etc. The use of fabric to deploy electrical components results in wearable electrical/computing devices and makes it easier to move with computing devices with less consumption of human energy and effort. Moreover the flexibility of fabric provides the opportunity to modify the shape to conform to new requirements of applications. The relative position of components, including sensors, actuators and processing elements, can be altered (Uddin, 2006).

In a nutshell, there are some exciting developments happening in the textiles area, and the whole wellbeing sector – although still a niche – is becoming stronger. Current trends lie in developing 'functionalized' surfaces, using new materials and coating technologies as well as integrating active ingredients. Work is also progressing to develop extremely light,

highly breathable, elastic, water-repellent as well as absorbent textiles, as barriers against infectious agents and solid particles. Apart from sensor technology, research is also being carried out on the use of radio frequency identification technology (RFID) integrated into textiles. This technology supports hospital logistics, for instance the location of equipment or even people.

10.4 Research and development in new products

The potential of intelligent textiles is huge. One can think of many applications for each of the examples given earlier. The other way around, starting from an application, the basic concepts have to be defined and evaluated for their use in or as a textile product. Selection of materials, structures and production technologies is the first step in the design. The actual research phase will be long and hard in many cases. Basic items that need to be addressed to come to a real breakthrough and to innovate are as follows:

- Transformation and conversion mechanisms to define the basic concept
- New materials
- New structures that can offer the requested functions.

Conductive materials, metals as well as conducting polymers, are already being used in many applications: antistatic working, EMI shielding, heating, transport of electrical signals, etc. Inherently conducting polymers (ICPs) are fascinating, dynamic, and molecular systems suitable for application in many domains of intelligent clothing: polymer batteries, solar energy conversion, biomechanical sensors, etc. Some materials are already available, be it at laboratory level. Some substantial disadvantages are the instability of the polymer in the air, the weak mechanical properties and the difficult processing. However, in the United States one laboratory has managed to spin the first polyaniline fiber (Santa Fe Science and Technology Inc., Santa Fe, NM).

Another class of materials that will play a major role without any doubt in many intelligent clothes is optical fibers. They are well known from applications in electronics, but the range of deformations to deal with in textile applications is of a different order and causes problems that restrict the number of applications at present. In all these cases, control of quality and certification becomes much more important. Although the development of intelligent fabrics and smart fabrics is in the infancy stage, spread all over the world in different organizations and industries, the level of quality products produced and their quality certification, etc., all become crucial for further research and development in these new products.

10.5 Types of testing: shape memory effect

10.5.1 Definition and significance of shape memory effect

The 'shape memory effect' (SME) is a special behavior of temperature-stimulating shape memory polymers, which are a special class of adaptive materials that can convert thermal energy directly into mechanical work. This phenomenon occurs when one of these special class of polymers is mechanically stretched at high temperature, typically 20°C above the glass transition or crystal melting temperature (T_g/T_{ms}), and cooled down to low temperatures, then heated above the critical transition temperature (T_g/T_{ms}), which results in the restoration of the original shorter 'memory' shape of the specimen (Lendlein and Kelch, 2002). The important properties which are considered for this shape memory effect are the thermomechanical properties of the thermoplastic polymer, such as shape fixity, shape recovery, and recovery stress and recovery speed (Tobushi *et al.*, 2001). These materials have two phase structures, namely the fixing phase, which remembers the initial shape, and the reversible phase, which shows a reversible soft and rigid transition with temperature.

10.5.2 Shape memory effect of fabrics

Materials with the unique property of reverting to their original, permanent shape from a fixed temporary shape only upon being triggered by an external stimulus are classified as demonstrating the shape memory effect. Fabrics treated with these materials can be called shape memory fabrics. The distinction between shape memory fabrics and wrinkle-free fabrics can be explained as follows. A wrinkle-free fabric has good elasticity because it can recover after release of the forces that cause deformations. Thus wrinkle-free finishing improves the elasticity of a fabric and can be called elastic finishing. Wrinkle-free fabric is not temperature sensitive and cannot recover its original shape when its temperature has been changed. On the other hand, shape memory fabrics, depending on the chemical used, can have lower, similar or higher (different levels of) elasticity than wrinkle-free fabrics at room temperature such as home laundering and body temperature environment, and recover their original shape, such as a flat appearance on which the fabric has no wrinkle. Shape memory fabrics can recover their original shape based on the use of shape memory polymers (SMPs) under certain conditions (temperature variation). This phenomenon can be called thermal elastic finishing or shape memory finishing, because the fabric can recover its original shape (elasticity) at higher temperature (thermal energy triggering), which leads to the shape memory effect. At the same time, shape memory fabrics probably have even better

elasticity at higher temperature than below the switch temperature. Thus, when a fabric has some residual wrinkles after removing external forces at room temperature, it can further recover its original shape at higher temperatures in tumble drying and/or machine laundering. So shape memory fabrics can doubly ensure the recovery of wrinkles when they are properly finished.

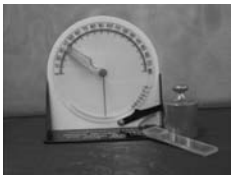
As a type of smart materials, shape memory polymers (SMPs) are increasingly drawing attention. At present, a good variety of polymers have been reported to show shape memory properties. But the different characterization or evaluation methods of shape memory properties and the varying conditions employed by different researchers have resulted in the reported properties of SMPs being basically not comparable. Therefore the relationship between shape memory properties and structures is not completely known for some species of SMPs. This may hinder the development of high-performance SMPs eventually. Furthermore, in contrast to the rapid increase in the numbers of SMPs, their application lags far behind, perhaps mainly because the current characterization of their properties cannot provide a comprehensive understanding for researchers. Therefore the evaluation of SMPs is crucial for their development and application.

10.6 Evaluation methods for shape memory fabrics

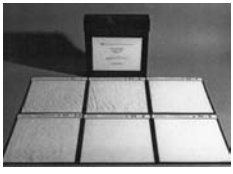
10.6.1 Wrinkle recovery, smoothness appearance, and crease retention

Several methods are available for measuring the wrinkled appearance of fabrics. For example, a subjective grading of wrinkles can be referenced from the AATCC test method 124-2001, 'Appearance of Fabrics after Repeated Home Laundering'; crease retention can be also subjectively graded by the AATCC test method 88C-2001, 'Retention of Crease in Fabrics after Repeated Home Laundering', and an objective evaluation of wrinkles can be carried out by the AATCC test method 66-1998, 'Wrinkle Recovery of Woven Fabrics: Recovery Angle'.

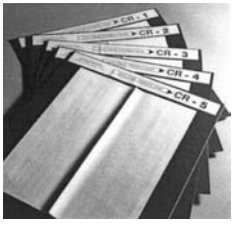
The AATCC test method 66-1998 (Wrinkle Recovery of Woven Fabrics: Recovery Angle) for accessing wrinkle recovery is applicable to fabrics made from any fibers, or combination of fibers. In this experiment, a test specimen is folded and compressed under controlled conditions of period and applied force to create a folded wrinkle. The test specimen is then suspended on a test instrument for a controlled recovery period, after which the recovery angle is measured (Fig. 10.1). The use of the wrinkle recovery test for measuring the crease angle and its recovery for shape memory fabrics is helpful for accessing the shape memory effect, because the original angle of the crease, and the recovery crease angle after the fabric is deformed,



10.1 Accessories for the AATCC test method 66-1998.



10.2 Accessories for the AATCC test method 124-2001.



10.3 Accessories for the AATCC test method 88C-2001.

must be obtained in advance. In our case, a function taking into account the temperature effect is needed to describe the shape memory effect of the fabrics, due to the fact that they have the recovery effect triggered by the change in environmental temperature.

The AATCC test method 124-2001 (Appearance of Fabrics after Repeated Home Laundering) is designed to evaluate the smoothness appearance of flat fabric specimens after repeated home laundering by simply looking at them. The fabric is graded by comparing with some scored standard fabrics with different surface appearances (Fig. 10.2). Any washable fabric and fabrics having different structures (woven, knit and non-woven) can be evaluated for smoothness appearance using this method.

The AATCC test method 88C-2001 (Retention of Crease in Fabrics after Repeated Home Laundering) is designed to evaluate the retention of pressed-in creases in fabrics after repeated home laundering (Fig. 10.3). Any washable fabric and fabrics of any structure may be evaluated for crease

retention using this method. The techniques for creasing are not outlined, since the purpose is to evaluate fabrics as they are supplied from manufacture or as ready for use. Furthermore, application of the creasing technique depends upon the fabric properties.

In recent years, Yang and Huang (2003) have developed a method for fabric 3-D surface reconstruction using a photometric stereo method. The 3-D surface of an AATCC standard wrinkle pattern is reconstructed and its wrinkle degree is measured using four index values indicating the variation of the surface height. The result suggests that there is a good linear correlation between the index value and the wrinkle degree of the pattern.

However, many evaluations of shape memory fabrics still rely on the traditional standard methods. Hashem *et al*. (2003) reported that the crease angle recovery and strength date were correlated with the amount of add-on polyelectrolyte. The authors developed methods of forming the ionic cross-links of cotton to provide crease angle recovery performance without the potential for releasing low molecular weight reactive materials like formaldehyde. The result was evaluated by crease angle according to the AATCC standard test method 66, and the breaking strength from Instron tensile tester according to the ASTM test method D1682 (Standard Methods of Test for Breaking Load and Elongation of Textile Fabrics, 1972). It was found that crease angle recovery could be imparted to cellulose fabric by the application of ionic cross-links. Carboxy-methylated woven fabric treated with cationized chitosan shows significant increases in wrinkle recovery angle without any strength losses. Also, fabric treated simultaneously or sequentially with 3-chloro-2-hydroxypropyl trimethyl ammonium chloride (CHTAC) and either chloracetic acid (CAA) or sodium chloromethyl sulfonate (CMSA) improved the wrinkle recovery angle and strength.

10.6.2 Primary parameters for testing of shape memory polymers

To characterize the shape memory properties of polymers, a set of parameters are desired. Firstly, the parameters should be able to reflect the nature of polymers. Secondly, distinguished from other properties of materials, shape memory properties are shown through a series of thermomechanical cyclic processes. Therefore the parameters should be able to define the whole shape memory processes as well. Lastly, the design of the parameters should pay attention to the potential applications. In view of these considerations, some parameters have been proposed and quantified (Tobushi *et al*., 2001; Kim and Lee, 1996; Li *et al*., 1998). In the following, these parameters are introduced.

Shape fixity

As has been described in the foregoing sections, when a shape memory polymer is heated up to a temperature above the transition temperature for triggering shape memory behavior (T_{trans}) (Lendlein and Kelch, 2002), it can develop large deformations which can be mostly fixed by cooling to a temperature below T_{trans}. This parameter was proposed to describe the extent of a temporary shape being fixed in one time of shape memorization (Tobushi *et al*., 2001; Kim and Lee, 1996; Lendlein and Kelch, 2002). It should be noted that various confusing usages of notation or even expression have taken place in the characterization of SMPs. As for shape fixity, other terms such as strain fixity (Tobushi *et al*., 2001) and shape retention (Lee *et al*., 2001) also represent the same physical meaning. Shape fixity (R_f) equals the amplitude ratio of the fixed deformation to the total deformation, which is given by:

$$\text{Shape fixity} = \frac{\text{fixed deformation}}{\text{total deformation}} \times 100\% \qquad 10.1$$

Shape fixity is related to both structure of polymers and the thermomechanical conditions of shape memorization. Compared with the structures of SMPs, the thermomechanical conditions play an equal or even more important role in determining the shape fixity and other shape memory properties.

Shape recovery

An SMP holding a deformation at low temperature can restore its original shape by being heated up above T_{trans}. Shape recovery (R_r) reflects how well an original shape is memorized when shape memorization occurs (Tobushi *et al*., 2001; Kim and Lee, 1996; Lendlein and Kelch, 2002). As with shape fixity, there are diverse and confusing usages not only in terms of notation but also in mathematical expressions for this parameter. Tobushi *et al*. (2001) utilized thermomechanical cyclic tensile tests to evaluate SMPs and entitled the parameter 'shape recoverability' or 'strain recovery'. In their study, the physical meaning represented by this parameter was interpreted as:

$$\text{Strain recovery} = \frac{\text{deformation to sample recovered in this cycle}}{\text{deformation to sample taken place in one cycle}} \times 100\% \qquad 10.2$$

Kim and co-workers also employed thermomechanical cyclic tensile tests to evaluate SMPs and defined the parameter as 'shape recovery' (Kim and Lee, 1996). The definition was given by:

$$\text{Shape recovery} = \frac{\text{deformation to sample recovered in a whole cycle}}{\text{deformation to sample taken place in the first cycle}} \times 100\% \quad 10.3$$

Li *et al*. (1998) utilized the bending test to investigate SMPs. Their definition of recovery rate could be understood as:

$$\text{Recovery rate} = \frac{\text{deformation to sample recovered in reheating process}}{\text{fixed deformation}} \times 100\% \quad 10.4$$

It is evident from equations 10.2–10.4 that the three forms of definition indeed represent different physical meanings even though they can all reflect the shape recovery from a particular angle. As a consequence of the different definitions, different values for the shape recovery will be obtained from the different formulae. For example, in the case of equation 10.2, shape recovery will increase with increasing cycle number and tend to 1, while in the case of equation 10.3 it will simply increase with increasing cycle number. Therefore caution should be taken in calculating shape recovery. Like shape fixity, shape recovery depends both on the structure of the polymers and on the thermomechanical conditions of shape memorization.

Recovery stress

Recovery stress stems from the elastic recovery stress generated in the deformation process. When SMPs are heated and deformed, elastic stress is generated, and the elastic stress is stored when SMPs are cooled down below T_{trans}. If deformed and fixed SMPs are reheated above T_{trans} the stress stored in them is released as shape recovery stress. In this regard, shape memorization can be looked at as a thermomechanical cycle consisting of stress generation, stress storage and stress release.

SMPs are considered to be promising in the development of smart actuators. The characterization of shape recovery stress is therefore essential. However, few attempts have been made to investigate shape recovery stress. Tobushi *et al*. (2001) investigated shape recovery stress through a specially designed thermomechanical cyclic tensile test on a shape memory material testing machine consisting of a tensile machine accompanied by a constant temperature chamber. Tey and co-workers studied the recovery process of the shape memory polyurethane foam MF-5520 produced by MHI (Tey *et al*., 2001). The shape memory polyurethane foam was compressed at 83°C and was cooled to room temperature (about 30°C) to keep deformation. Then the deformed foam was heated gradually and the change of recovery stress as the temperature increased was investigated. Liang and co-workers investigated the recovery stress of the MM-4500 SMP from

Mitsubishi Heavy Industries (MHI) (Liang *et al*., 1997). A heat gun was used to heat the specimens (short-duration heating, so there was no apparent creep), and the temperature was estimated in the range of 70–80°C.

The dilemma in characterization of recovery stress of SMPs is chiefly caused by the viscoelasticity of the polymers, especially for thermoplastic SMPs. Owing to the limitations of the equipment and the efficiency of heat transfer, it is practically impossible to heat or cool an SMP to a certain temperature in a sufficiently short time in experiments. Therefore the stress relaxation is inevitable if only the SMP is in a constrained state. As a consequence, the stress generated in deformation must be lost to some extent in the shape fixing and shape recovery processes. Additionally, the rate of stress relaxation alters with temperature change in the whole shape memory process, resulting in its influence on recovery stress being unknown. In other words, the recovery stress may change all the time while undergoing stress relaxation and the progress of change is uncertain. Therefore it is difficult to capture or calculate the recovery stress in absolute terms. Actually, in practical applications, the influence of the viscoelastic behavior will also be inevitable. So if the experimental conditions are constant and the experimental results are thereby reproducible, the measurements of recovery stress in relative terms are valuable. The author carried out some investigations into the recovery stress of SMPs through a specially designed thermomechanical cyclic tensile test.

Shape recovery speed

Shape recovery speed describes the speed at which a given SMP recovers from a temporary shape to its original shape when heated. Actually, the parameter has no uniform and clear name. In the study of Li *et al*. (1998) it was called the 'speed of recovery process', while Luo *et al*. (1997) entitled it 'deformation recovery speed'. Here the author proposes the name 'shape recovery speed' as its title, which is in parallel with the other shape memory properties, to make it easy to memorize. The parameter can be measured both qualitatively and quantitatively.

Liu *et al*. (2002) investigated the shape recovery process of some SMPs and qualitatively studied the shape recovery speed using a video camera at a rate of 20 frames per second. It was evident that the SMP restored its original shape in 0.7 s. Li *et al*. (1998) and Luo *et al*. (1997) investigated the shape recovery of SMPs with a constant heating rate. Through the curve of shape recovery as a function of temperature, the shape recovery speed was calculated. The shape recovery speed can be defined as:

$$V_r = \frac{dR_r}{dT} \times \frac{dT}{dt} \qquad 10.5$$

where V_r is the shape recovery speed, dR_r/dT is the ratio of shape recovery to temperature, and dT/dt is the heating rate.

10.6.3 Factors affecting shape memory effect

Lendlein and Kelch (2002) pointed out that the shape memory effect was not related to a specific material property of single polymers; it rather resulted from a combination of the polymer structure and the polymer morphology together with the applied processing and programming technology. The shape memory effect (SME) of SMPs is shown through the whole thermomechanical cyclic processes involving deformation, shape fixing and shape recovery. Each process may change the shape memorization and affect the shape memory properties eventually. Changing the conditions in the thermomechanical cyclic processes would lead to variation of the shape memory properties. Different methods and conditions employed in previous reports have resulted in difficulties in comparing the experimental results. It is necessary to characterize the SME with varying conditions in order to provide important information for development and application of SMPs.

The author and her group conducted a number of experiments on the effects of deformation conditions on the SME and found that conditions such as deformation temperature, maximum strain and deformation rate had a profound effect on the SME. In addition the effects of fixing conditions on the SME were also analyzed. Parameters such as fixing rate and fixing temperature were the main conditions that affected the SME. The author also investigated the effects of recovery conditions on the SME. In this case the recovery temperature and recovery time were very important conditions which affected the SME. Shape memory properties are dependent on the special microstructures of SMPs. Therefore the elements affecting the microstructure will definitely influence the shape memory properties. It was supposed that the processing temperature may affect the microstructure, such as morphology, micro-domain structure and phase separation, that determines the shape memory properties of SMPs. Besides processing temperature, the environmental conditions can also play an important role on the shape memory properties. Yang *et al*. (2004) studied the influence of water on the microstructure and shape memory properties of SMPU MM3520 from Mitsubishi Heavy Industries (MHI). It was found that the SMPU loses its shape fixing capability after being exposed in the air at room temperature (about 20°C) for several days. In addition, for the evaluation of shape memory materials, the conditions of sample preparation have a great influence on the test results.

10.7 Thermal regulation property of phase change materials

10.7.1 Definition and significance of thermal regulation property

Phase change materials (PCMs) are able to absorb, store and release large amounts of latent heat over a defined temperature range when the material changes phase or state. A fabric containing a PCM can act as a transient thermal barrier which regulates the heat flux. The heat absorption by PCMs results in a delay in microclimate temperature and hence a substantial decrease of the amount of sweat produced by the skin of the wearer. Both lead to an enhancement of the wearing comfort and prevent heat stress (Bendkowska *et al*., 2005).

Fabrics incorporated with MicroPCM are called 'PCM treated fabrics' or just 'PCM fabrics'. The thermal properties of PCM fabrics are dynamic and responsive. That is, their thermal properties are related to the change of temperature and time. For example, when the environment temperature reaches the PCM melting point, the physical state of the PCM in the fabric will change from solid to liquid along with the absorption of heat, while the temperature of the PCM in the fabric keeps constant at melting point, therefore it can regulate its temperature automatically by itself. As the reverse thermal regulation performance occurs during the cooling process, the environment temperature comes to its freezing point. So, the PCM fabric can provide a cooling effect caused by heat absorption of the PCM and a heating effect caused by heat emission of the PCM to the human body.

PCM fabrics are designed to be used under special environmental conditions in which they need to offer a desired temperature lasting for a definite period of time. Hence, thermal properties during phase change are very important because once the PCM fabric's temperature goes out of the phase change range, it is no longer effective as an active thermal wear. In order to evaluate the thermal properties of PCM fabrics, some research has been conducted. Pause (1995) developed the concept of dynamic thermal insulation to measure the transient effect on the insulation value of PCM fabrics, and pointed out that the total insulation of PCM fabrics is comprised of basic insulation and dynamic thermal insulation that was determined from the duration of the temperature variation during the phase change. The dynamic thermal insulation was calculated by comparing the times for achieving the end temperature of the phase change range of the samples with and without MicroPCM and with reference to the basic thermal insulation of the samples. The thermal insulation is given in units of thermal resistance. In 2002, a new test instrument and measurement

index were described by Hittle and Andre (2002). The index of temperature regulation factor (TRF) is used to indicate the temperature-regulating ability of PCM fabrics, which is a dimensionless number less than or equal to 1, and the TRF for PCM fabrics will always be less than the TRF for non-PCM fabrics. A test for PCM garments was carried out by Shim and McCullough (2001) in a warm and a cold chamber. The value of heat loss from a thermal manikin was measured and used to quantify the effect of PCMs in clothing on heat flow from the body during temperature transients.

Fabrics containing PCM microcapsules present a unique challenge to the standard test procedures used for determining the thermal properties of fabrics. In the case of traditional fabrics, the thermal properties are investigated by standard steady-state procedures involving the use of guarded hot plate apparatus. A steady state procedure is inadequate in assessing the dynamic performance of fabrics containing PCMs, because PCM is a highly productive thermal storage medium (Bendkowska, 2006).

10.7.2 Primary parameters for testing

By analyzing the physical mechanisms of heat and moisture transfer through textiles incorporating phase change materials, Ying *et al*. (2004) proposed three indices and related test methods to characterize the thermal functional performance of PCM fabrics. They are the static thermal insulation (I_s), the thermal regulating capability (I_d and Δt_d) and the thermal psychosensory intensity (TPI).

The indices of thermal regulating capability (I_d and Δt_d) are used to describe the thermal regulating performance of textiles incorporating phase change materials, and were found to be strongly dependent on the amount of phase change material. From the aspect of thermal comfort of textiles and clothing, the TPI index is used to represent the thermal psychosensory intensity perceived by the body, and the TPI value increases with increase of phase change material level. The static thermal insulation index (I_s) is used to describe the static thermal insulation effects of the textiles. All indices can be measured and calculated by using the testing methods of the Fabric Intelligent Hand Tester.

When there exist gradients of temperature and water vapor pressure across a textile structure, heat and moisture transfer through the structure occur. These two kinds of transportation involve multiple processes under different conditions. By combining the mechanisms of heat and moisture transfer in porous textiles and the phase change process occurring in microcapsules incorporated in the textile, a new mathematical model for the processes has been provided by Li and Zhu (2006). The factors involved in this new model include the heat of moisture sorption or desorption of vapor

by fibers, the heat of moisture sorption or desorption of liquid water by fibers, the heat of evaporation of water, the heat change by conduction, the heat related to radiation, and the latent heat which is gained and lost from the MicroPCM. For the process of phase change, the factors of the quantity of PCM and the radius of the MicroPCM spheres have been considered in the model. From the model, it is seen that both factors have a significant influence on the heat energy changes through porous textiles. Thus, the greater the quantity of PCM added, the higher the volume fraction and the more heat energy is gained or lost from the MicroPCM. Therefore, more heat flux is delayed through the PCM fabrics and a stronger thermal regulation performance occurs; also, the smaller the radius of the MicroPCM spheres, the more significant the thermal regulating capability of the porous textile (Li and Zhu, 2006).

With the testing conditions used, no liquid phase is involved and no radiation factors are considered, so the energy balance equations given by Li and Zhu can be simplified. They become

For PCM fabrics:

$$c_{\mathrm{V}} \frac{\partial T}{\partial t} = \lambda_{\mathrm{V}} \frac{\partial (C_{\mathrm{f}} \varepsilon_{\mathrm{f}})}{\partial t} + \frac{\partial}{\partial x}\left[K_{\mathrm{mix}} \frac{\partial T}{\partial x} \right] - q(x,t) \qquad 10.6$$

For non-PCM fabrics:

$$c_{\mathrm{V}} \frac{\partial T}{\partial t} = \lambda_{\mathrm{V}} \frac{\partial (C_{\mathrm{f}} \varepsilon_{\mathrm{f}})}{\partial t} + \frac{\partial}{\partial x}\left[K_{\mathrm{mix}} \frac{\partial T}{\partial x} \right] \qquad 10.7$$

where x denotes the coordinate across the porous textile slab; $x = 0$ and $x = L$ indicate the positions at the lower and upper surfaces of the porous slab, respectively; T is the temperature of the flow fields at x in the porous textile; c_{v} is the volumetric heat capacity of the fabric (kJ/m^3 K); λ_{v} is the heat of sorption or desorption of vapor by fibers (kJ/kg); C_{f} is the water vapor concentration in the fibers of the fabric (kg/m^3); K_{mix} is the thermal conductivity of the fabric (W/m K); and ε_{f} is the volume fraction of fibers.

The relationship between the porosity of the fabric (ε), the volume fraction of fibers (ε_{f}), and the volume fraction of MicroPCM (ε_{m}) is expressed by equation 10.8 under the test conditions:

$$\varepsilon + \varepsilon_{\mathrm{f}} + \varepsilon_{\mathrm{m}} = 1 \qquad 10.8$$

In equation 10.6 the first term on the right-hand side describes the heat of moisture sorption or desorption of vapor by fibers, the second term describes the heat change by conduction, and the last term, $q(x,t)$, describes the latent heat which is gained or lost from the MicroPCM. The above analysis of the physical mechanisms of heat and moisture transfer through PCM and non-PCM fabrics leads to the introduction of three indices and test methods which characterize the thermal functional performance of fabrics.

The static thermal insulation (I_s)

Equations 10.6 and 10.7 show that the temperature and moisture gradually reach equilibrium with the environment, and then $\partial T/\partial t = 0$ and $\partial(C_f\varepsilon_f)/\partial t = 0$. For the PCM fabrics, in the equilibrium state, the phase change will have happened, so the term $q(x,t) = 0$. Therefore, in this state, equations 10.6 and 10.7 are identical and the heat flux value becomes constant, i.e.

$$K_{\text{mix}} \frac{\partial T}{\partial x} = \text{const.} \tag{10.9}$$

Defining this constant to be the index I_s, which represents the static thermal insulation effects of the fabric, given in units of heat flux (W/m^2), the defining equation is written as:

$$I_s = K_{\text{mix}} \left.\frac{\partial T}{\partial x}\right|_{x\in[L-\delta L, L]} \tag{10.10}$$

The static thermal insulation can also be expressed by equation 10.6:

$$I_s = -\frac{h_t}{\varepsilon}(T - T_{ab}) \tag{10.11}$$

where T_{ab} is the constant environment temperature (K), and h_t is the convection heat transfer coefficient.

The thermal regulating capability (I_d and Δt_d)

The thermal regulating capability of PCM fabrics is dependent on temperature and time. It takes place only during the temperature range of the phase change and terminates when the phase change in all the MicroPCM contained in the fabrics is complete. Comparing equations 10.6 and 10.7, it can be seen that the thermal regulating capability is related to the term $q(x,t)$. Suppose the duration time of the phase change process in the PCM fabrics is from $t_{d1}$to t_{d2}, hence, the indices Δt_d and I_d may be defined as:

$$\Delta t_d = t_{d2} - t_{d1} \tag{10.12}$$

and

$$I_d = \frac{\int_{t_{d1}}^{t_{d2}} q(L,t)\,\mathrm{d}t}{t_{d2} - t_{d1}} \tag{10.13}$$

I_d is the mean of the heat flux delayed by phase change during the phase change period, and the total heat energy change related to phase change is expressed by $\Delta t_d * I_d$.

Thermal psychosensory intensity

From the aspect of thermal comfort of textile and clothing, Ring and de Dear (1991) proposed that the intensity of thermal sensations (termed the psychosensory intensity, PSI) is proportional to the cumulative total impulses from stimulus onset at the thermoreceptor until such time as the receptor firing rate has decayed to within one impulse per second of the poststimulus steady state. On this basis, Wang *et al.* (2002) derived equation 10.14 to calculate the impulse frequency of the thermoreceptors responding to heat flux and temperature profile in the skin:

$$Q(y,t) = C + K_s T_{sk}(y,t) + K_d \frac{\partial T_{sk}(y,t)}{\partial t} \qquad 10.14$$

where K_s and K_d are the static and dynamic differential sensitivity, C is a constant, y is the location of the thermoreceptors (depth from the skin surface), and T_{sk} is the temperature of the skin. In equation 10.14, the values of C, K_s and K_d are taken as 28.1 (s^{-1}), 0.72($s^{-1} \cdot °C^{-1}$) and –50($°C^{-1}$), respectively.

For the PCM fabric, the index of thermal psychosensory intensity (TPI) is defined to express the thermal perception by the body. In the test conditions, the temperature measured at the surface of the fabric, $T(L,t)$, is taken as equal to T_{sk}; therefore, equation 10.14 becomes

$$Q(L,t) = C + K_s T(L,t) + K_d \frac{\partial T(L,t)}{\partial t} \qquad 10.15$$

From the curves generated from equation 10.15, TPI is the integral of $Q(L,t)$ over the time from t_{d1} to t_{d2}, i.e.

$$\text{TPI} = \int_{td1}^{td2} Q(L,t)\,\mathrm{d}t \qquad 10.16$$

The above three parameters can be effectively utilized to measure the thermoregulatory response of a fabric treated with a PCM material. However, different treatment methods and fabric constructions may require additional tests to be conducted to fully understand the thermal functional performance of the fabrics.

In an attempt to determine the thermal regulating ability of fabrics containing phase change materials, Bendkowska *et al.* (2005) developed an instrument to measure the temperature regulating factor (TRF) (see Fig. 10.4). Determination of the TRF of apparel fabrics was done by means of the instrument, which used a dynamic heat source. This instrument simulated an arrangement of skin–apparel–environment. The fabric sample was sandwiched between a hot plate and two cold plates, one on either side of the hot plate. These cold plates at a constant temperature simulated the environment outside the apparel. Sinusoidally varying heat input to the hot

10.4 General view of apparatus for testing thermoregulation properties of fabrics containing PCMs (Bendkowska *et al.,* 2005).

plate simulated human activity. To measure the steady-state thermal resistance of the fabric (R) the controlled heat flux was constant and the test proceeded until a steady state was reached. To assess the temperature regulating ability, the heat flux was varied sinusoidally with time and the TRF was determined.

10.8 Self-cleaning testing

The development of permanent self-cleaning cotton textiles with a life cycle of 25–50 washings or more is an objective sought by the textile industry in the framework of new products classified as intelligent textiles. These self-cleaning fabrics have a nanofilm coating of titanium dioxide nanoparticles, which can break down dirt molecules, pollutants and microorganisms when exposed to visible and UV light. Clothes made using this method could be cleaned by simply exposing them to sunlight.

10.8.1 Self-cleaning effect

The self-cleaning fabrics work using the photocatalytic properties of titanium dioxide, a compound used in many new nanotechnology solar cell applications. The fabric is coated with a thin layer of titanium dioxide particles that measure only 20 nanometers in diameter. When this semi-conductive layer is exposed to light, photons with energy equal to or greater than the band gap of the titanium dioxide excite electrons up to the conduction band. The excited electrons within the crystal structure react with oxygen atoms in the air, creating free-radical oxygen. These oxygen atoms are powerful oxidizing agents, which can break down most carbon-based compounds through oxidation–reduction reactions. In these reactions, the organic compounds (i.e. dirt, body odor, smoking odor, etc., bacteria, color stains, harmful organic materials such as formaldehyde, other carbon-based molecules, pollutants and micro-organisms) are broken down into substances such as carbon dioxide and water. Since the titanium dioxide only acts as a catalyst to the reactions, it is never used up. This allows the coating to continue breaking down stains over and over.

As the technology of self-cleaning is relatively new and not yet well established among researchers, the test methods for testing these fabrics are not yet standardized. The researchers who have been developing these fabrics adapted their own techniques to analyze the effectiveness of the coatings and self-cleaning capability of the fabrics. Several techniques have been reported. In one of the studies on the development of self-cleaning cotton, Qi *et al*. (2006) used a surface characterization technique to assess the performance of the cloth. The structure and morphology of these coatings were investigated using field emission scanning electron microscopy (FESEM, JSM-6335F at 3.0 kV, JEOL, Tokyo, Japan). The crystallinity of solid powder extracted from the sols was studied by X-ray diffraction spectroscopy (XRD, Bruker D8 Discover X-ray diffractometer) operating at 40 kV and 30 mA. The crystallinity of the titania coatings formed on the cotton fabric was studied by low angle X-ray diffraction (XRD, Philips Xpert XRD system) with incident beam at 3 u using Cu Ka radiation and detector scan mode operating at 40 kV and 30 mA. The UV absorption of coated cotton substrates was measured according to the Australian/New Zealand Standard AS/NZS 4399:1996 using a Varian Cary 300 UV spectrophotometer. In the absence of standard test methods, the following test procedures have been suggested by the researchers.

10.8.2 Test for static bactericidal activities

One of the important tests that is carried out for assessing the self-cleaning ability is the testing for static bacterial activities. The test may be done on fabric swatches for each test specimen (woven cotton and TiO_2 coated cotton fabrics) with a diameter of 5 cm, stacking up and placing in separate 150 ml wide-mouth jars. 1 ml of inoculum is added to each jar. The tops are immediately screwed tightly to prevent evaporation. For the '0 h' contact time sample, 100 ml of sterile phosphate buffer may be added immediately after inoculation and the jars are shaken for one minute. 1 ml of the resulting solution is transferred from each jar to a test tube containing 4 ml of double distilled water ddH_2O and plated out in duplicate. For the '5 h' contact time sample, the jars are incubated for 5 h in a 37°C incubator before the plate count technique is performed. All the Petri dishes are incubated for 24 h in a 37°C incubator. After incubation, the number of viable cells (colonies) is counted manually and the results after multiplication with the dilution factor can be expressed as mean colony forming units (CFU) per ml after averaging the duplicate counts (Qi *et al*., 2006).

10.8.3 Test for decomposition activities of colorant stains

The decomposition activities of colorant stains are assessed by analyzing the decrease in concentration of the colorants during exposure to UV

irradiation. To carry out this test, a 3 g coated woven white cotton fabric is cut into 1 cm × 1 cm pieces. These pieces are placed in a 250 ml beaker containing 75 ml Neolan Blue 2G aqueous solution (0.2 g l^{-1}), 100 ml Cibacron Blue F-R (0.2 g l^{-1}) and uncoated white cotton fabric as well as a comparison. Then the beakers are exposed to UV irradiation provided by Philips UV lamps (20 V) while vigorously shaken (IKA KS260 Basic Orbital Shaker). The light intensity on the top of the beakers is 1.2–1.3 mW cm^{-2}. Prior to UV irradiation, the colorant solution with white cotton pieces is kept in dark conditions for 4 h while shaking to establish the absorption–desorption equilibrium. UV-Vis absorption spectra of irradiated samples are recorded on a UV-Vis spectrometer (Perkin Elmer UV-Vis spectrometer Lambda 18). The colorant solution is centrifuged to precipitate cotton fibers at the bottom of the tube and the upper clear colorant solution is used. The changes in concentration of colorants are estimated by the concentration at the absorption peak for Neolan Blue 2G at 630 nm and for Cibacron Blue F-R at 610 nm (Qi *et al*., 2006).

10.8.4 Test for degradation activities of colored stains

This test may be carried out to assess the effectiveness of removal of colored stains on the fabric. An example of the evaluation of degradation activities of a red wine stain and a concentrated coffee stain is presented. The test involves using cut pieces of dimensions 4.5 cm × 6.5 cm pieces of woven white cotton and S60 coated woven white cotton fabrics respectively. A red wine stain and a coffee stain are dropped respectively on coated white cotton fabrics as well as pristine white cotton for comparison. The irradiation of all samples may be carried out in the cavity of a Suntest solar simulator on Xenotest Alpha LM light exposure and weathering test instrument (air-cooled xenon arc lamp, irradiance 45–95 mW cm22, Xenotest Alpha LM, Heraeus Industrietechnik, Hanau, Germany). The red wine and coffee stained cotton fabrics may be irradiated for 8 h and 20 h respectively (Qi *et al*., 2006). The discoloration is observed before and after the treatment and may be quantified using spectrophotometric studies.

10.8.5 Test for tearing strength

The tearing strengths of pristine woven cotton and titania coated cotton before and after 20 h of light irradiation may be measured by an Elmendorf Tearing Tester (Thwing-Albert Instrument Co.) in accordance with ASTM D1424-96. The tearing strength results are analyzed before and after irradiation treatment for coated samples. Further, in an interesting study on self-cleaning of wool–polyamide and polyester textiles by TiO_2-rutile modification under daylight irradiation at ambient temperature, Bozzi *et al*. (2005) have discussed the self-cleaning evaluation of wool–polyamide and

polyester textiles by elemental analysis and dust test. Elemental analysis of the TiO_2-loaded textile fabrics was carried out by atomic absorption spectrometry using a Perkin-Elmer 300 S unit. A flow of dust was applied on the textiles and the dust adherence was estimated from color changes of the textile surface in a relative scale of 1–5.

An irradiation procedure and evaluation of textile cleaning performance by gas chromatography has been reported by Meilert *et al*. (2005). The photochemical reactor consisted of 80 mL cylindrical Pyrex flasks containing a strip of textile of 48 cm^2 positioned immediately behind the wall of the reactor. The irradiation of the samples was carried out in the cavity of a Suntest solar simulator (Hanau, Germany) air-cooled at 45°C for 24 h. The Suntest lamp had a wavelength distribution with 7% of the photons between 290 and 400 nm and was provided with a cut-off filter at 310 nm. The profile of the photons emitted between 3100 and 800 nm followed the solar spectrum with a light intensity of 50 mW/cm^2 corresponding to 50% of AM 1, the light intensity of the midday equatorial solar radiation. The CO_2 produced during the irradiation was measured in a gas chromatography apparatus (Carlo Erba, Milano) provided with a Poropak S column. In addition, the authors used attenuated total reflection infrared (ATR-IR) spectroscopy, elemental analysis techniques and transmission electron microscopy techniques to analyze the loading of TiO_2 on the textile fabrics and to understand the cross-sectional behavior of treated fabrics.

10.8.6 Applications of self-cleaning fabrics

In addition to suits, the new self-cleaning coating could be applied to hospital garments, sportswear, military uniforms and raincoats. Other possible applications include awning material for outdoor campers, fabrics for lawn furniture and convertible tops for cars. The coating could appear in consumer products within five years, the researchers estimate.

10.9 Electronic responsive testing

Electronic textiles or e-textiles lead to an interdisciplinary field of research which brings together specialists in information technology, microsystems, materials and textiles. The focus of this new area is on developing the enabling technologies and fabrication techniques for the economical manufacture of large-area, flexible, conformable information systems that are expected to have unique applications for both consumer electronics and the military industry.

Electronic textiles combine the strengths and capabilities of electronics and textiles. E-textiles, also called smart fabrics, have not only ‘wearable’

capabilities like any other garment, but also local monitoring and computation, as well as wireless communication capabilities. Sensors and simple computational elements are embedded in e-textiles, as well as built into yarns, with the goal of gathering sensitive information, monitoring vital statistics and sending them remotely (possibly over a wireless channel) for further processing. Possible applications include medical (infant or patient) monitoring, personal information processing systems, and remote monitoring of deployed personnel in military or space applications.

Conductive fabrics are gaining popularity amongst electronic textiles. In general, two main methods are followed for rendering a textile material electrically conductive: (a) by applying a conductive coating on the surface of a non-conductive textile after it is formed, or (b) by incorporating conductive fibers (e.g. via interweaving or embroidery) into the textile structure. Any textile structure, including knitted, woven and non-woven textiles, can be thus made electrically conductive. The choice of the textile structure and of the conductive mechanism determines the efficiency of the textile as an equivalent electroconductive material and assures its durability for its intended lifetime. The state of the art in conductive fibers is highly conductive metal wires or plated fibers. Inherently, conductive polymers are becoming closer in performance to metallic conductors and may be suitable for the next generation of applications in electrotextiles.

As these fabrics are new inventions in the field of intelligent textiles, complex approaches have been adapted to integrate these fabrics with conductive wires (conductive fabrics), wearable electronic devices and microcomputers. Accordingly, the testing of these fabrics varies among different researchers. In the absence of standard test methods and procedures, a brief review of the testing approaches adopted by different researchers is presented in the following sections. Some textile products with electrical properties have already found application in the field of EMI shielding, static dissipation and resistive heaters. For these products, the whole area of the fabric has to be conductive, whereas data transmission requires separate conductor lines. For data transmission it is important to have high conductivity.

In order to evaluate the electrical and electronic response of conductive fabrics, Kirstein *et al*. (2002) measured the high-frequency properties of conductive fabrics to predict the electrical properties of different textiles and to optimize the fabrics and the signal line configurations. They analyzed a plain woven fabric with copper filaments. The electrical characterization was performed by measuring material properties such as dielectric permittivity, transmission line configuration and impedance measurement. To investigate the frequency characteristics of textile transmission lines they measured the transmission properties with a vector network analyzer (VNA) up to 6 GHz.

A means of characterizing electrotextiles using a unique waveguide measurement using imbalanced coupling has been reported by Ouyang and Chappell (2005a, 2005b). By using waveguide measurement, the authors measured the change in quality factor, Q, and the resonance frequency to determine the loss tangent and the dielectric constant of the material. In order to characterize the conductive property of various conductive fibers, a fiber fixture for the waveguide cavity measurement was created. With the fiber fixture, conductive threads were arranged parallel to each other with controllable equal space over the aperture of the waveguide in the measurement setup. In this way, the effective surface resistance of different classes of conductive threads was evaluated at high frequency without the pattern affecting the result. Two methods of measuring effective surface resistance and conductivity of different classifications of electrotextile were presented. A waveguide technique is applicable for materials that are metal-plated after forming the textile. A high-Q waveguide cavity-based measurement technique is desired to enhance the sensitivity of the effect of conductivity in order to characterize the electrotextile properties. Measuring Q of a cavity to obtain metal conductivity is well established for traditional measurements with symmetric input and output ports. In addition to the waveguide cavity measurement, the authors utilized another measurement technique for characterizing the electrotextile based on the microstrip resonator.

In general, to evaluate the electronic response of fabrics, the researchers used the following electrical parameters to describe the behaviour of signal transmission in such fabrics.

10.9.1 Transmission line configuration

This transmission line configuration is similar to conventional coplanar waveguides (CPW) on printed wire boards.

10.9.2 Impedance measurement

This parameter is used to investigate the characteristic impedance of the textile transmission lines. It is expected that the textile geometric variations influence the impedance. The signal reflections along the transmission line can be measured with time domain reflectometry, as the metal fibers incorporated in conductive fabrics show different impedance characteristics and signal transmission effects.

10.9.3 Frequency characterization

In order to determine the bandwidth of textile transmission lines, the frequency characteristics of textile transmission lines are investigated and

transmission properties with a network analyzer working at up to 6 GHz are measured. The extracted frequency characteristics reveal information such as dielectric and ohmic losses and the line insertion losses.

10.9.4 Digital signal transmission

Testing of digital signal transmission with a line length of 20 cm and a clock signal with a frequency of 100 MHz may be carried out to understand the signal integrity of different line configurations. The more signal lines, the better the signal integrity, but the more energy is needed for transmitting the signal.

10.10 Applications

In the last few years, smart/intelligent materials and structures have found a wide application as novel smart products in aerospace, transportation, telecommunications, homes, buildings and infrastructures. Today smart textiles are being used in the space programme, in skiwear, shoes, sports helmets and insulation devices as heat generating/storing fibers/fabrics. In addition, smart fabrics integrated with optical fiber sensors have been used to monitor the soundness of major bridges and buildings. It is possible to incorporate sensors inside the garments and these fabrics can detect information regarding injury to and health of the wearer. Textiles in fiber, film and foam forms made of shape memory polymers result in a range of high-performance fabrics and garments in a variety of applications. Fiber sensors, which are capable of measuring temperature, strain/stress, sensing gas, biological species and smell, are typical smart fibers that can be directly applied to textiles. Conductive polymer-based actuators have achieved very high levels of energy density. Textile scaffolds can be made from biodegradable fibers and can be used as biological tissues and organs such as ears and noses. It is possible to impart very high-energy absorption capacity to textiles integrated with nanomaterials and they can be used for stain proofing, abrasion resistance, light emission, etc.

10.10.1 Smart textiles/apparel

The term ‘smart textiles’ is derived from intelligent or smart materials. The concept of ‘smart material’ was first defined in Japan in 1989. The first textile material that, in retroaction, was labelled as a ‘smart textile’ was silk thread having a shape memory effect. The continual shrinkage of the textile industry in the Western world has amply raised the interest in intelligent textiles. Smart textile products meet all the criteria for high added-value technology allowing transformation to a competitive high-tech industry: from resource-

based towards knowledge-based; from quantity to quality; from mass-produced single-use products to manufactured-on-demand, multi-use and upgradable product-services; from 'material and tangible' to 'intangible' value-added products, processes and services (Van Langenhove and Hertleer, 2004). An unlikely alliance between textile manufacturers, material scientists and computer engineers has resulted in some truly clever clothing. The interaction between woven fabric and electronics is finding favor in the world of interior design as well. Elsewhere, garment manufacturers are focusing on functional benefits rather than aesthetics. The simplest of these so-called 'smart clothing' items are made by adding the required circuitry, power sources, electronic devices and sensors to standard fabric garments. Batteries can be sewn into pockets, wires fed through seams, and wireless antennae attached to collars and cuffs. The design of such clothing items is still important, although appearance is not the sole criterion. Embedded sensors control conductive material on the back of the jacket to keep the wearer warm should identify the temperature drop, while electroluminescent wires are fixed to pockets and hems to light up in the dark as a safety feature. Such clothing doesn't exist simply to look good, or to attract attention, nor does it simply meet needs without regard to aesthetics.

A totally new vision could be possible with the advent of wearable electronic textiles, where functionality is incorporated into the fabric. More sophisticated prototypes for smart clothing use conductive threads to weave switches, circuits and sensors into the fabric itself. These threads can be made from very finely drawn conductive metals, metallic-coated or metal-wrapped yarns, or conductive polymers. Ideas touted to date include jacket sleeve keypads for controlling cellphones, pagers or MP3 players, and sportswear with integral fabric sensors and display panels, ideal for monitoring heart rate and blood pressure during a gym workout or morning run. Clothing fitted with textile Global Positioning System technology could also be suitable for locating skiers or mountaineers in bad weather or even for keeping a watch on young children (Gould, 2003).

Smart textiles are widely used in medical and hygiene-related products. Antimicrobial and odor-preventing fabrics find wide applications in activewear and underwear fabrics. These fabrics are hygienic and increase the performance of athletes. Another example of smart textiles that is an integral part of our daily life is 'airbag' fabrics in automobiles. The inflation/deflation mechanism of an airbag is a good example of sensible and intelligent response to mechanical shocks and vibrations.

10.10.2 Military garments

Textile-based materials equipped with nanotechnology and electronics have a major role in the development of high-tech military uniforms and

materials. Active intelligent textile systems, integrated with electronics, have the capacity of improving combat performance by sensing, adapting themselves and responding to a situational combat need, allowing the combat soldiers to continue their mission. Meantime, smart technologies aim to help soldiers do everything they need to do with less equipment and a lighter load.

Wearable computers – devices that are attached or integrated into an individual's clothing – were once considered useful mostly as bulky maintenance devices, but are now considered to be the electronic heart of the soldier in the future. The first wearable computers were developed for navigation and maintenance tasks. There are also military applications as body-worn computational resources for soldiers. Intelligent textiles can be used in uniforms to protect soldiers in extreme weather and to constantly monitor the wearer's physical condition. Some even claim automatic healing of wounds. Other outfits have the ability to adapt their color to the surroundings for camouflage purposes. The technology is also helping to improve law-enforcement and anti-terrorism efforts. Computers are being developed that are wired into clothing and have the capability to track enemy targets, network the soldier with air, land and sea forces, monitor his or her physical health, and even translate native languages. Devices are in production that will aid law enforcement and military personnel in the global war on terrorism.

A soldier on the battlefield, an athlete on the training track, a patient in the home – every aspect of their physiology can be remotely monitored by the clothing they are wearing. In short, the ability to weave new-technology threads of electronic wizardry into fabrics means that the IQ of textiles is rising sharply. First-generation commercial techniques for producing electronic textiles included impregnating textiles with carbon, incorporating metal filaments. But this new generation of 'gifted garments' gets its brains from conductive polymers, a special class of organic polymers capable of conducting electricity. For soldiers in the field wearing such a 'smart garment', the weight they carry is significantly reduced as much of their communications technology is integrated into their uniform. That same intelligent textile technology can also be used to provide warmth in cold weather, and to monitor constantly their physiology and the air they breathe – and even to render them invisible to radar.

Much of the smart-fabric, 'soldier of the future' research is centered at the US Army Soldier Systems Center in Natick, Massachusetts. The scientists and technologists are tackling a variety of textiles that can transport power and information. One example is a soldier sticking his or her intelligent glove finger into water to see if it is safe to drink. The soldier could communicate with others by a fabric keyboard that might be either unrolled from the pocket of a uniform, or simply sewn or woven in as part of the uniform's sleeve.

If electronics and optical technologies could be integrated successfully into textiles, there could be a striking improvement in battlefield communications. One such project, the Battle Dress Uniform, gives soldiers camouflage and environmental protection, but it also may become a wearable electronic network to send and receive data.

10.10.3 Medical uses

Smart textiles are widely used in medical and hygiene-related products. Antimicrobial and odor-preventing fabrics find wide applications in activewear and underwear fabrics. These fabrics are hygienic and increase the performance of athletes.

At present, there are some applications in the medical field whose thermal performance can be significantly improved using textiles treated with PCM microcapsules. Such applications include the following.

Surgical clothing

Surgical clothing such as gowns, caps and gloves is often worn for several hours at a time in the operation room. Because these materials are designed primarily to prevent permeation of particles and liquids, which carry bacteria, the thermophysical comfort of such garments is usually poor. But the thermophysical comfort of these garments can be improved substantially by coating the inside of the garments with PCM microcapsules. This effect results from the PCM reacting to any temperature change in the microclimate by either absorbing or emitting heat so that thermoregulation occurs. This thermoregulating effect is responsible for the garments' enhanced thermophysical comfort.

Bedding materials

PCM may also be used in bedding materials such as mattress covers, sheets and blankets, as well as for improving comfort in hospitals, for example. Using materials treated with PCM microcapsules to stabilize the thermoregulation of the patient's microclimate may also support the healing process. Blankets made of acrylic incorporating PCMs and mattresses covered with a PCM microcapsule coating are already available in the marketplace.

Materials used in intensive care

A further development of this technology may center on products used in intensive care units with which a sustained and intensive cooling benefit

can be realized. This would serve to remove excess heat generated by the patient's body after an operation. Another possible PCM application may be a product which supports efforts to keep the patient warm enough during an operation by providing insulation tailored to the body's temperature.

10.10.4 Protective garments/uniforms

Application of PCM and shape memory polymers in textiles has opened up a number of applications in protective garments. In protective garments, PCMs absorb surplus body heat to keep the body cool. They provide the insulation effect caused by heat emission of the PCM into the fibrous structure and the thermoregulating effect provided by these materials maintains the microclimate temperature nearly constant. Shape memory polymer coated or laminated materials can improve the thermophysical comfort of surgical protective garments, bedding and incontinence products because of their temperature-adaptive moisture management features (Hu and Mondal, 2006). PCMs incorporated in non-woven protective garments can be used to control or to treat hazardous waste. Safety helmets with PCMs can have very good thermal resistance and the heat generated by the wearer can be dissipated only by convection, which results in substantial reduction of the microclimate temperature in the head area. In the case of chemical or biological protective clothing, a conflict between the protective function of the clothing and the physiological regulation of body temperature can be solved by PCMs which provide significant microclimate cooling for 1–3 hours under usually high heat conditions. This cooling apparel uses macro-encapsulated PCMs uniformly distributed within lightweight vests, helmet liners, cowls and neck collars (Bendkowska, 2006).

10.11 Future trends

Intelligent or so-called 'smart' clothing represents the future of both the textile/clothing industry and the electronic industry. As the convergence between these two industries brings great opportunities and challenges, it draws attention and investment from many organizations in different fields, e.g. academic institutions, government organizations, private companies and laboratories. Currently, none of the applications of smart clothing is considered a full integration of high technology and fashion design, since most research attempts are focusing on solving technical problems such as integrating microchip and computer systems into clothing or overcoming wash-and-care issues. Consequently, the current applications are unable to attract the mass market. The unbalanced contribution from the electronics and fashion industries and the users is the main problem for smart clothing

development at this stage. Moreover, the research reveals that the strategic thinking which helps in defining true benefits or core values of smart clothing that may lead to better outcomes is still lacking. As the approach has recently changed from the technical one to a user-centered one, strategic thinking and a new product development process addressing key elements from both industries are required. As a result, the key question is identifying and optimally balancing these key elements in the new approach and the new product development process. Nevertheless, fashion design and product design are established fields of their own and it is difficult to adopt or switch to the other's work methods. Therefore, the new approach and the new product development process should encourage the development team to think in a different way and go beyond their current creative boundaries.

10.11.1 Integrated testing and standardization

The technology of intelligent fabrics and clothing is growing fast. The application of intelligent fabrics in technical textiles, protective clothing (fire brigade, police, military clothing) and medical textiles is considered to be very promising. Current developments in R & D of intelligent fabrics are resulting in applications of these fabrics in sports and automobiles. As the need for these textiles is increasing, there is an absolute need to develop an integrated testing system to evaluate the performance of these textiles. Intelligent fabrics and clothing do not belong to just one particular field but result from combined research in several areas, such as electronics, electrical, textiles, thermodynamics, computing, etc. Hence the characteristics of these fabrics differ and the testing of these fabrics should address these issues. Test methods must be adapted to evaluate several properties of fabrics such as heat regulation, thermal comfort, shape memory effect and sensory properties in addition to the regular textile properties. The R & D efforts in this direction must aim at developing testing methods to integrate several characteristics of these smart fabrics so that a complete analysis may be possible. In addition, efforts to develop testing standards for several properties of these fabrics and clothing would be a great move for the benefit of industry and research organizations.

10.11.2 Interdisciplinary approach

Intelligent textiles provide rich evidence of the enormous wealth of opportunities still to be grasped by the textile industry. These opportunities appear equally abundant in the clothing and fashion sector of the industry and in the technical textiles sector. The development of a full intelligent textile product needs a strongly interdisciplinary approach. Such an approach would combine the efforts of several people involved in disciplines other

than textiles and clothing. In particular, future developments will arise from active collaboration between people representing a whole variety of backgrounds and disciplines, including electrical, electronics, mechanical, textile, biotechnology, non-technology engineering streams, materials science, process development, design, commerce and marketing. Such an effort will provide the intelligent clothing industry with the opportunity to work together with innovative partners from various other disciplines and thus contribute to a further switch or increased demand for these innovative fabrics for technical, medical, safety, military and fashion sectors.

10.12 Conclusions

Intelligent fabrics will undoubtedly feature strongly in textile developments over the next decade and look set to become more and more part of everyday life. They represent a variety of different types of fabrics and garments incorporating specially constructed polymers, electronic devices or even some types of colorants. Smart clothing is perceived as the next generation of both fashion and electronic products. Its influence is rising dramatically, as indicated by the rapid increase in research and development projects in the last five years. It offers a wide range of possibilities and opportunities for new business and new product lines. As a result, research and product developments have been carried out by multinational companies and leading academic institutes. Testing the various characteristics of these fabrics becomes an important aspect of everyone concerned in the field. Research and development is growing fast in this direction to evaluate these fabrics for successful application in the industry. Although several research groups are working in this area, there is an urgent need for them to coordinate their efforts to set new testing methods and standards to analyze the various characteristics of these fabrics in order to fully utilize them for the said purpose. An understanding between fashion designers and manufacturers of intelligent fabrics would help in designing more and more new products for consumers. This demands a totally new approach for testing and evaluation of these fabrics, to include testing several properties, not just one. Such an integrated approach would greatly help in understanding these new materials in order to increase their scope of application. In this direction, all the research groups should work in conjunction to set up new standards and test methods to assess the performance of these new products which are going to significantly influence our everyday lives.

10.13 Sources of further information and advice

Intelligent textiles and clothing have attracted several research groups working in different countries and organizations. They are all aiming at

developing new products to be eventually used in the industry successfully. However, many are in the infancy stage and some patented technologies are available to be used by the industry. Important research groups are North Carolina University, the Institute of Textiles and Clothing at Hong Kong Polytechnic University, Shinshoo University in Japan, Tampere University in Finland, the Indian Institute of Technology at Delhi, the Wearable Computing Lab at Zürich, Switzerland, and many other individuals in various scientific organizations and industries.

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